Update On $K_{L,S} \rightarrow \pi^+\pi^-\gamma$

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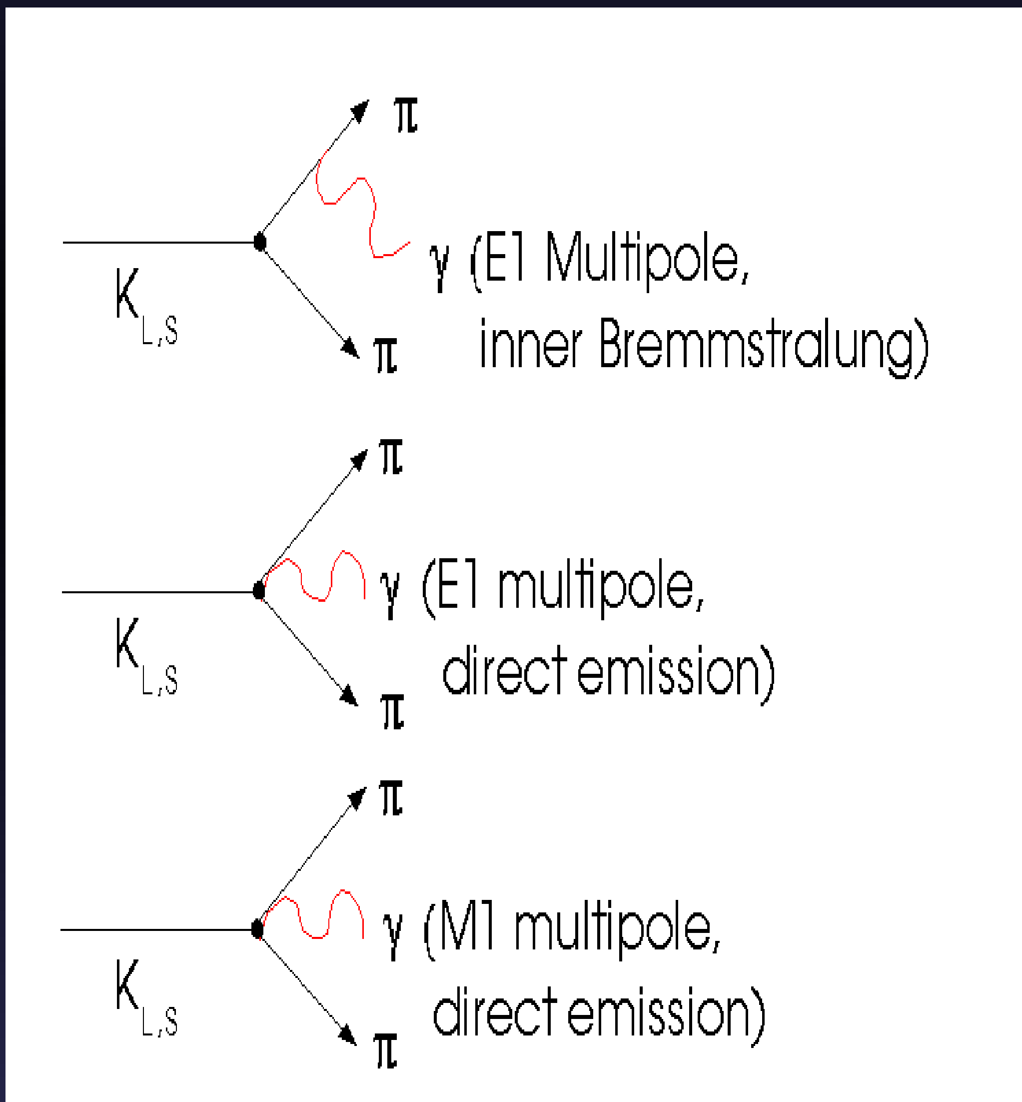
Outline For Today

- Brief Review of the Physics involved
- Discussion of the $K_{L,S} \to \pi^+\pi^-\gamma$ event generator
  - Review of the current technique
  - Introduction of new method
- Data/MC comparisons
- Conclusion

Review of $K_{L,S} \to \pi^+\pi^-\gamma$

- Looking for *new* direct CP violation in this mode.
  - This new amount of direct CP violation would arise from *part* of the E1 direct emission amplitude for the K_L
  - Measuring $\eta_{+-\gamma} \neq \eta_{+-}$ is a sign of new direct CP violation
  - $\eta_{+-\gamma} = \varepsilon + \varepsilon' + \varepsilon'_{+-\gamma} =$ (indirect+"old" direct + "new" direct) CP violation

Diagrams Contributing To $K_{L,S} \to \pi^+\pi^-\gamma$



CP conserving for K_S
CP violating for K_L

CP conserving for K_S
CP violating for K_L

CP violating for K_S
CP conserving for K_L

- The amplitudes for the previous diagrams are:

$$E_{IB}(K_S) = \left(4\frac{M_K^{\,2}}{E_\gamma^2}\right)\frac{e^{i\delta_0}}{1-\beta^2\cos^2(\theta)}$$

$$E_{IB}(K_L) = \left(4\frac{M_K^{\,2}}{E_\gamma^2}\right)\frac{\eta_{+-}\; e^{i\delta_0}}{1-\beta^2\cos^2(\theta)}$$

$$M(K_L) = i\left|g_{M1}\right|\left(\frac{a_1/a_2}{M_\rho^2 - M_K^2 + 2E_\gamma M_K} + 1\right)e^{i\delta_1}$$

$$E_{DE}(K_S) = \frac{\left|g_{E1(i)}\right|}{\left|\epsilon\right|}e^{i\delta_1}$$

$$E_{DE}(K_L) = \left|g_{E1(i)}\right|e^{i(\delta_1+\phi_\epsilon)} + i\left|g_{E1(d)}\right|e^{i\delta_1}$$

Indirect CP Violation

Direct CP Violation

- The difference between $\eta_{+-\gamma}$ and η_{+-} is given by :

$$\epsilon'_{+-\gamma}=\frac{1}{\Gamma_{K_S\to\pi^+\pi^-\gamma}}\int d[PS]\,\tilde{\epsilon}'_{+-\gamma}\left|E_{IB}(K_S)+E_{DE}(K_S)\right|^2$$

where

$$\tilde{\epsilon}'_{+-\gamma}=\hat{\epsilon}\,e^{i\left(\delta_1-\delta_0+\frac{\pi}{2}\right)}\left(2\frac{E_\gamma}{M_K}\right)^2\left(1-\beta^2\cos^2(\theta)\right)$$

and

$$\hat{\epsilon}=\frac{g_{E1(d)}}{16}$$

- $\hat{\epsilon}$ is a pure measure of “new” direct CP violation

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$K_{L,S} \to \pi^+\pi^-\gamma$ Event Generation- Old Method

- The default version of the MC generates $\pi^+\pi^-\gamma$ events in two steps:
  - First, choose proper lifetime, and thus z-vertex, according to :

$$\frac{dN}{d\tau} \propto |\rho|^2 e^{-\frac{\tau}{\tau_s}} + |\eta_{+-\gamma}|^2 (1+r) e^{-\frac{\tau}{\tau_L}}$$

$$+2|\eta_{+-\gamma}||\rho| \cos(\Delta m \tau + \phi_\rho - \phi_\eta) e^{-(\frac{1}{\tau_L}+\frac{1}{\tau_S})\frac{\tau}{2}}$$

Old Method Part 2

– Next, choose the type of emission using the probabilities:

$$P(IB) \quad \propto \quad |\rho|^2 e^{-\frac{\tau}{\tau_s}} + |\eta_{+-\gamma}|^2 e^{-\frac{\tau}{\tau_L}} + 2|\eta_{+-\gamma}||\rho| \cos(\Delta m \tau + \phi_\rho - \phi_\eta) e^{-(\frac{1}{\tau_L}+\frac{1}{\tau_S})\frac{\tau}{2}}$$

$$P(DE\ via\ M1) \quad \propto \quad |\eta_{+-\gamma}|^2 r\, e^{-\frac{\tau}{\tau_L}}$$

– Then use the proper distributions for E_γ and $\cos\theta$ for the chosen emission type

Old Method Part 3

- The input parameters for this method are:
  - r : ratio of M1 to E1(IB+DE) emission in K_L
  - $K_S \to \pi^+\pi^-\gamma$ branching ratio
  - $\eta_{+-\gamma}$, or equivalently, $\varepsilon'_{+-\gamma}$
- These parameters contain various amplitude factors:
  - r arises mainly from M1 emission- >g_{M1}, a1/a2
  - the branching ratio is sensitive to $g_{E1(i)}$
  - $\varepsilon'_{+-\gamma}$ depends on $g_{E1(d)}$, and somewhat on $g_{E1(i)}$

Old Method Part 4

- Unfortunately, E1 DE isn't included in the old generator's photon spectrum.
- Also, it would be nice to make the dependence on the amplitude parameters explicit......

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$K_{L,S} \to \pi^+\pi^-\gamma$ Event Generation-New Method

- The simplest solution is to derive a statistical weight as a function of all three variables, which would allow events to be generated in a single step.
- Start with a more basic form of the lifetime distribution:

$$\frac{dN}{d\tau} \propto \left|\rho^2\right| \Gamma_{K_S \to \pi^+\pi^-\gamma} e^{-\frac{\tau}{\tau_s}} + \Gamma_{K_L \to \pi^+\pi^-\gamma} e^{-\frac{\tau}{\tau_L}}$$

$$+2\,Re\left[\rho\,\gamma_{LS}^{*}\,e^{i\Delta m_K \tau}\right] e^{-\left(\frac{1}{\tau_L}+\frac{1}{\tau_S}\right)\frac{\tau}{2}}$$

- Then differentiate with respect to photon energy and direction to yield:

$$\frac{dN}{d\tau\, dE_\gamma\, d\cos(\theta)} \propto |\rho^2| \left| \frac{d\Gamma_{K_S\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \right| e^{-\frac{\tau}{\tau_s}} + \left| \frac{d\Gamma_{K_L\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos\theta} \right| e^{-\frac{\tau}{\tau_L}}$$

$$+2\,Re\left| \rho \frac{d\gamma^*_{LS}}{dE_\gamma\, d\cos(\theta)} e^{i\Delta m_K \tau} \right| e^{-(\frac{1}{\tau_L}+\frac{1}{\tau_S})\frac{\tau}{2}}$$

where

$$\frac{d\gamma_{LS}}{dE_\gamma\, d\cos(\theta)} \propto \left[E_{IB}(K_L)+E_{DE}(K_L)\right] * \left[E^*_{IB}(K_S)+E^*_{DE}(K_S)\right] + M(K_L)\,M^*(K_S)$$

$$\frac{d\Gamma_{K_L\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \propto \left|E_{IB}(K_L)+E_{DE}(K_L)\right|^2 + \left|M(K_L)\right|^2$$

$$\frac{d\Gamma_{K_S\to\pi^+\pi^-\gamma}}{dE_\gamma\, d\cos(\theta)} \propto \left|E_{IB}(K_S)+E_{DE}(K_S)\right|^2$$

This is the new statistical weighting function !

New Method Part 3

- Now we have a technique that uses the amplitude parameters directly. I've written an event generator that uses this method, and it's running now.
  - It generates believable output
  - But it's ~15 times slower than the default generator.
    - We have enough computing power here at UVA to offset this disadvantage.

New Method Part 4

- This new weighting function has two added benefits:
  - The same function can be utilized for re-weighting
  - It can also be fit to the data in order to extract the amplitude parameters directly.
    - We could in principle fit both the regenerator and the vacuum beams the same way at the same time

New Method Part 5

- It may be desirable to fit the data twice, first to the traditional set of parameters r , the K_S branching ratio and $\eta_{+-\gamma}$ as well as the amplitude parameters g_{M1}, a1/a2, $g_{E1(l)}$, and $g_{E1(d)}$.
- The former can be calculated using the latter, so it would be easy to cross-check results.
  - The code needed for this now exists.

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DATA/MC Comparisons

- The following plots are of regenerator beam events from the full 97 data set. After all cuts, we are left with 70422 events. Background is ~0.4%.
- The number of Monte Carlo events remaining after cuts is 82240.
- Generation and analysis were carried out with Ktevana v6_01

Initialization Parameters For E832 Routines

- RECON832INI called for “K3PI”
- CSI832INI called with option 9 for 1GeV thresholds
- Default VTO832 settings used except:
  - EVTO_XCLUS_CUT = 1.0E9
- FID832INI defaults used.

Event Selection- Crunch Cuts

Cut Variable	***Remove Event If***	***Why?***
Reg Veto	Fires	
Reg Pb Veto	Fires	
RC Veto	Fires	
MA Veto	Fires	
ZVTX – z vertex	<100 or >160	
TRKEOP -E/p for tracks	>0.9	Electron Rejection
F832CA	<0.0	Want tracks inside CA
TRKP -track momentum	<7.0	Multiple scattering
Gamma Energy (Lab)	<0.90	
FUSECHI2CS-Fusion χ^2	>1.0e3	Want clean photon cluster
Pion-Photon Separation	<0.18	Prevent cluster overlaps
Kaon Energy	<10.0 or >180.0	
Kaon Mass	<0.460 or >0.540	
Kaon P_t^2	>0.005	

Event Selection- Analysis Cuts

Cut Variable	***Remove Event If***	***Why?***
KTSPILL(IPACK=1) IERR(1)	<> 0	Reject bad spills
INRUN	>10400 and <10430 =10356 =7594	Runs with no regenerator
INRUN	>9896 and <9909 =9884	Runs with 0.1 Gev pt-kick
RECON832 IERR	<> 0	Reconstruction error
MSK_L1VER832	<>0	L1 verification
FID832 IERR	<> 0	Fiducial cuts
TRKP(1) x TRKP(2)	>0	Want negative and positive tracks
T3FPI0	Returns $M_{\pi 0} \neq 0.0$	Suppress $\pi^+\pi^-\pi^0$ background

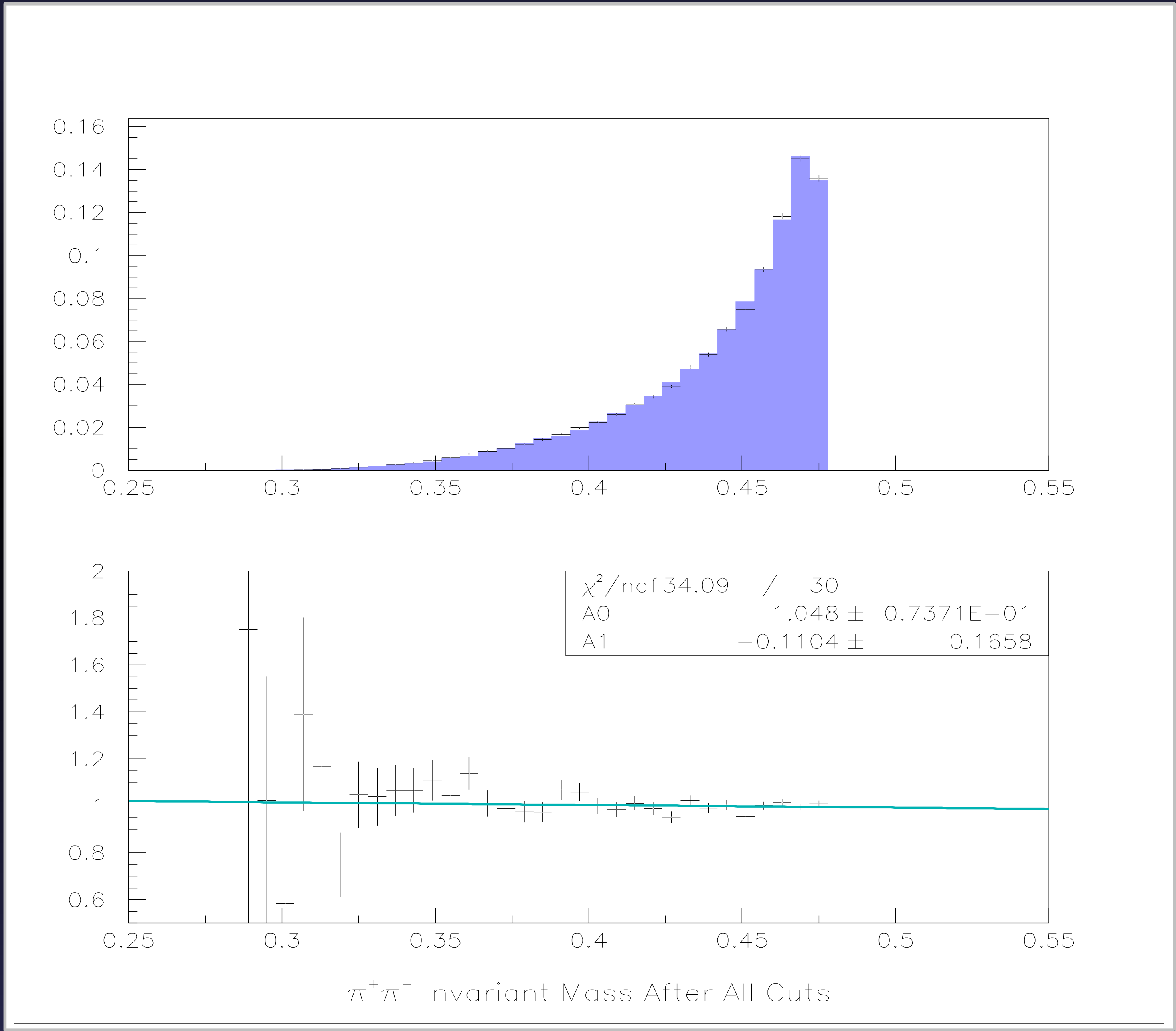
More Analysis Cuts

Cut Variable	*Remove Event If*	*Why?*
VTXZ -Z Vertex	<125.476 , >158.0	
Kaon Mass	< 0.48967 , > 0.50567	
Kaon P_t^2	> 2.5e-4	
$\pi+\pi-$ Mass	> 0.477	Suppress $\pi^+\pi^-$ background
E_γ in Kaon Center of Mass	< 0.02	
E_γ in lab	< 1.1	
PP0KINE- P_{π°	< -0.10 , > -0.005	Suppress $\pi^+\pi^-\pi^0$ background
Kaon Momentum	< 20.0 , > 160.0	
TRKEOP-E/p for tracks	> 0.85	Reject e^+ and e^-
TRKP-track momentum	<8.0	
VTXCHI - vertex χ^2	>50.0	
FUSECHI2CS-fusion χ^2	>48.0	
Λ Mass	No cut	
Proton Momentum	No cut	
TRKOCHI-track offset χ^2	>50.0	
Track Separation at CSI	< 0.03	
Photon-Track Separation at CSI	<0.30	
ISEEDRING	>18.1	
ISMLRING2	< 4.5	

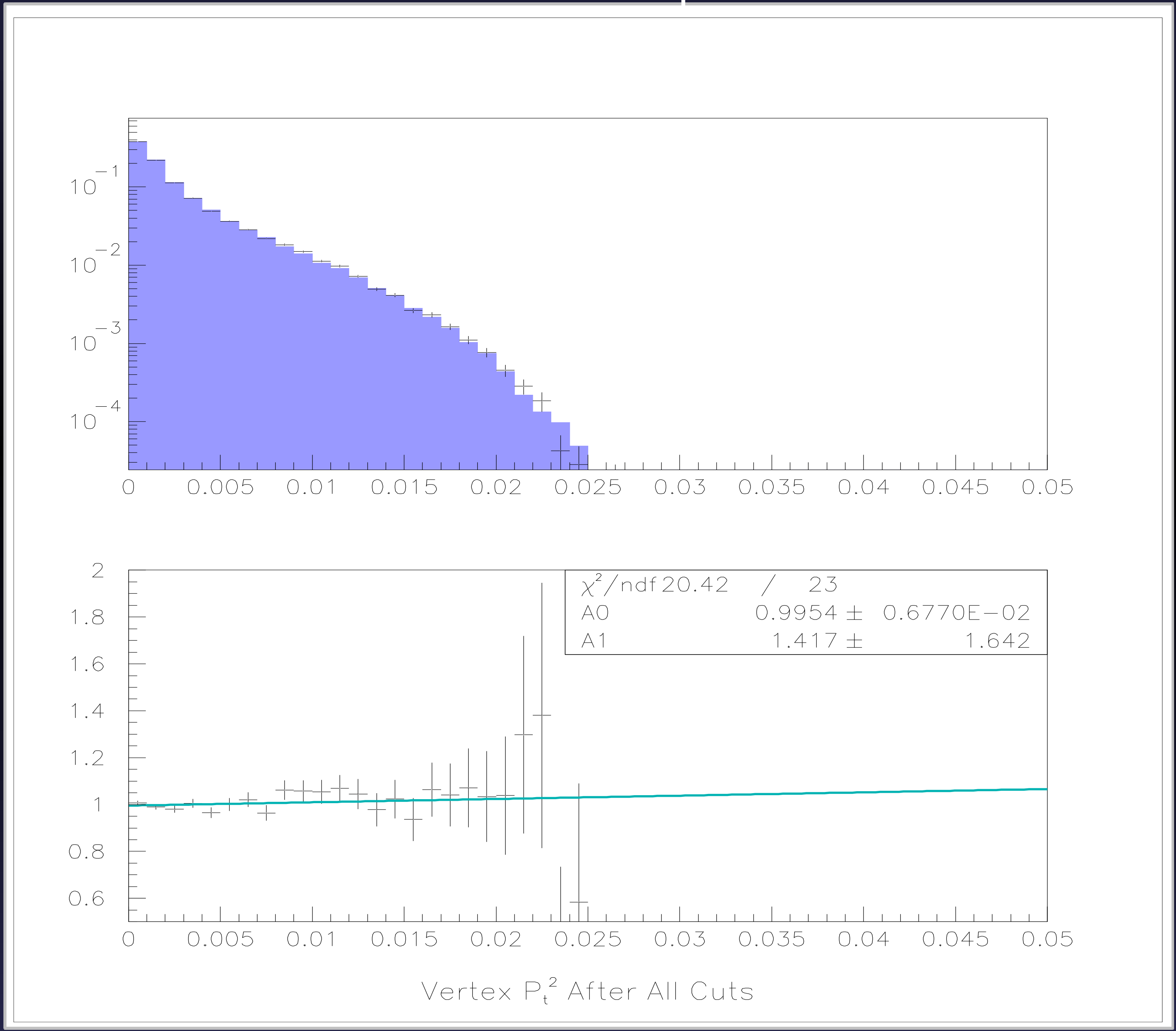
Monte Carlo Input Parameters

- The following values were used to generate monte carlo events:
  - $\eta_{+-} = 2.282 \times 10^{-3}$, $\Phi_{+-} = 43.6^{\circ}$ $\longrightarrow$ $\varepsilon' = 0$
  - $g_{M1} = 1.19$, $a1/a2 = -0.738$
  - $g_{E1(i)} = 0$, $g_{E1(d)} = 0$ $\longrightarrow$ $\eta_{+-\gamma} = \eta_{+-}$
- Strong interaction phase shifts are taken from K_{e4} data collected by E865.

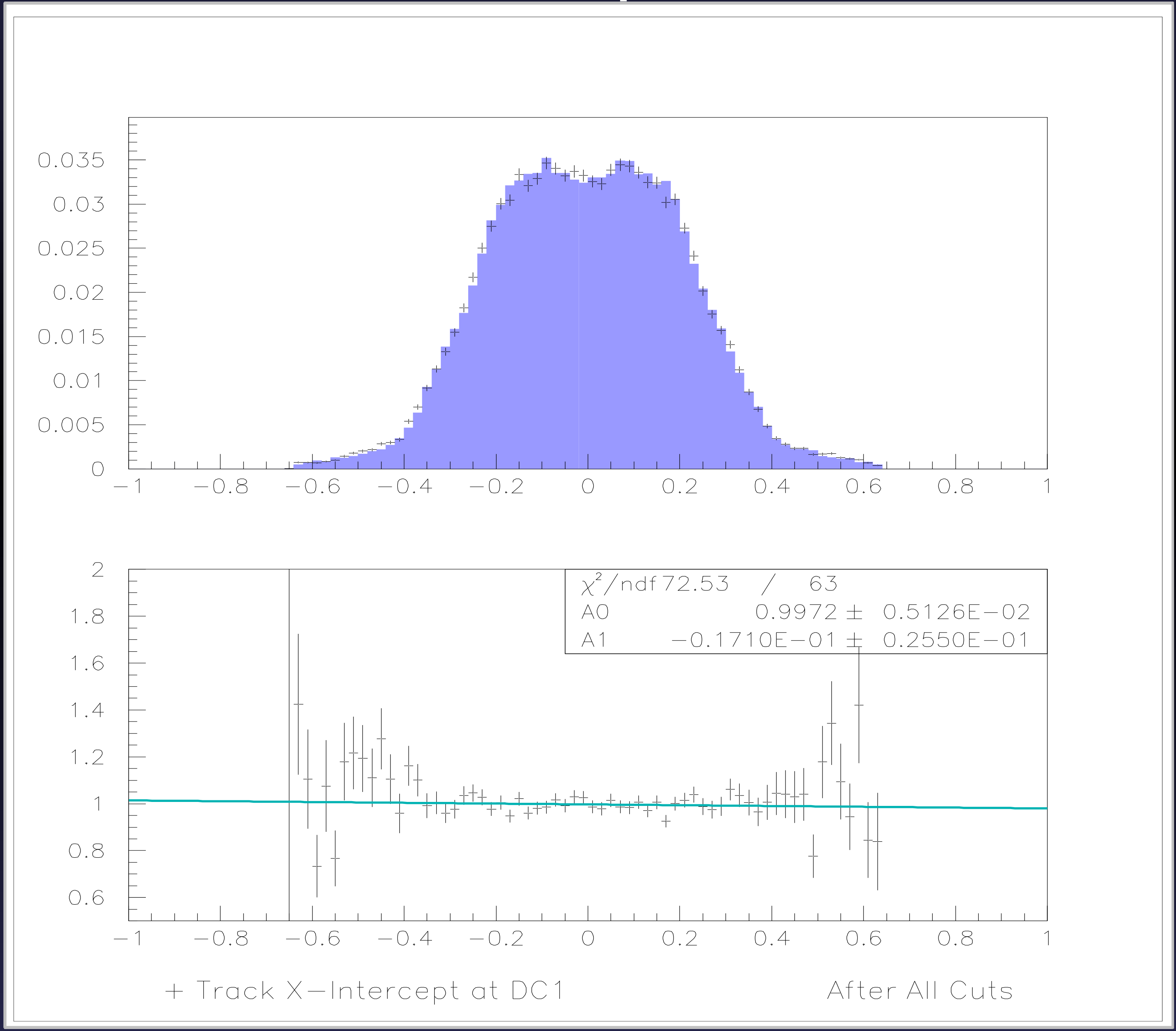
$\pi^+\pi^-$ Invariant Mass



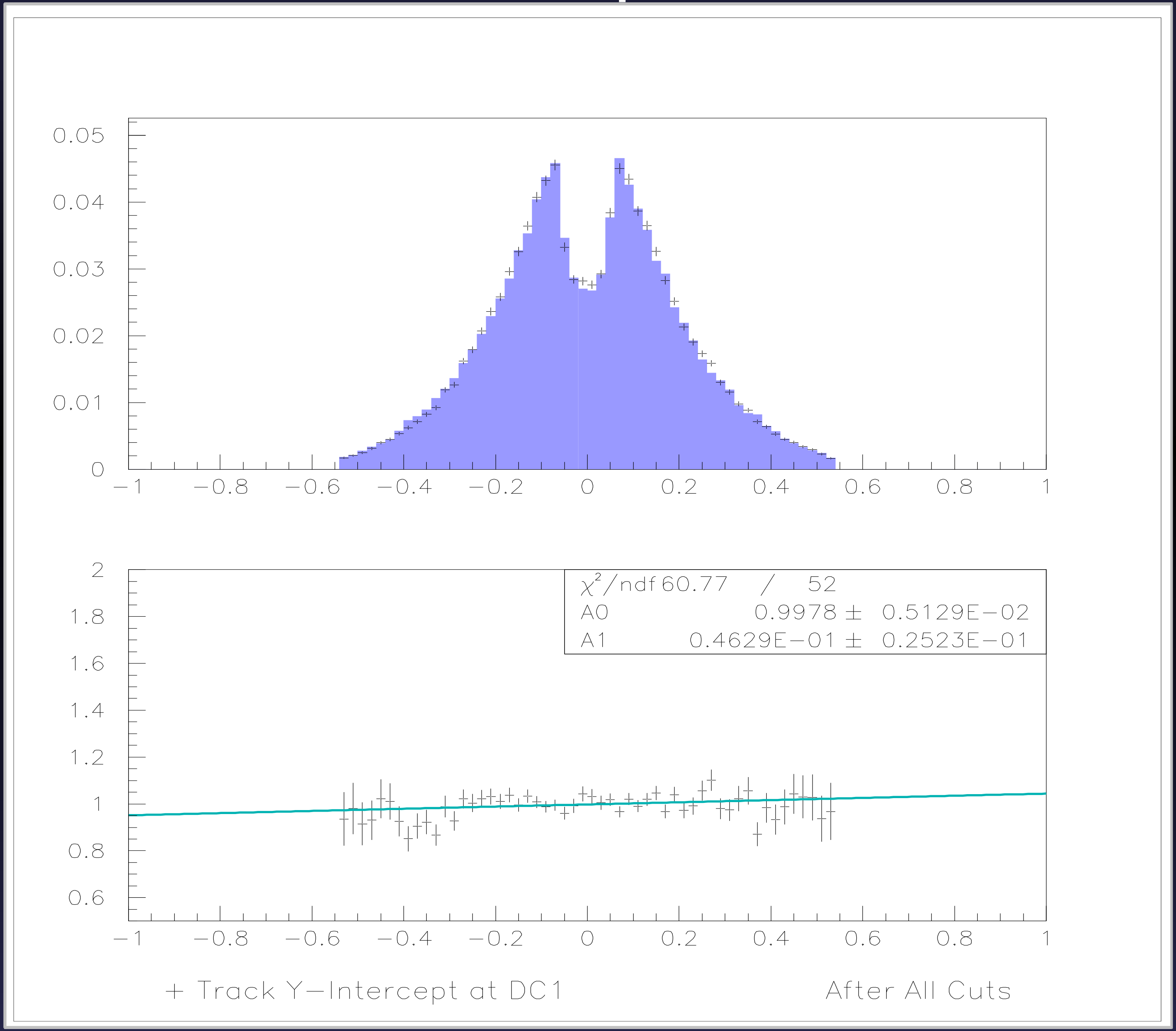
$\pi^+\pi^-$ P_t^2


10^-1
10^-2
10^-3
10^-4
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05
2
1.8
1.6
1.4
1.2
1
0.8
0.6
χ²/ndf 20.42 / 23
A0 0.9954 ± 0.6770E−02
A1 1.417 ± 1.642
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05
Vertex Pt² After All Cuts

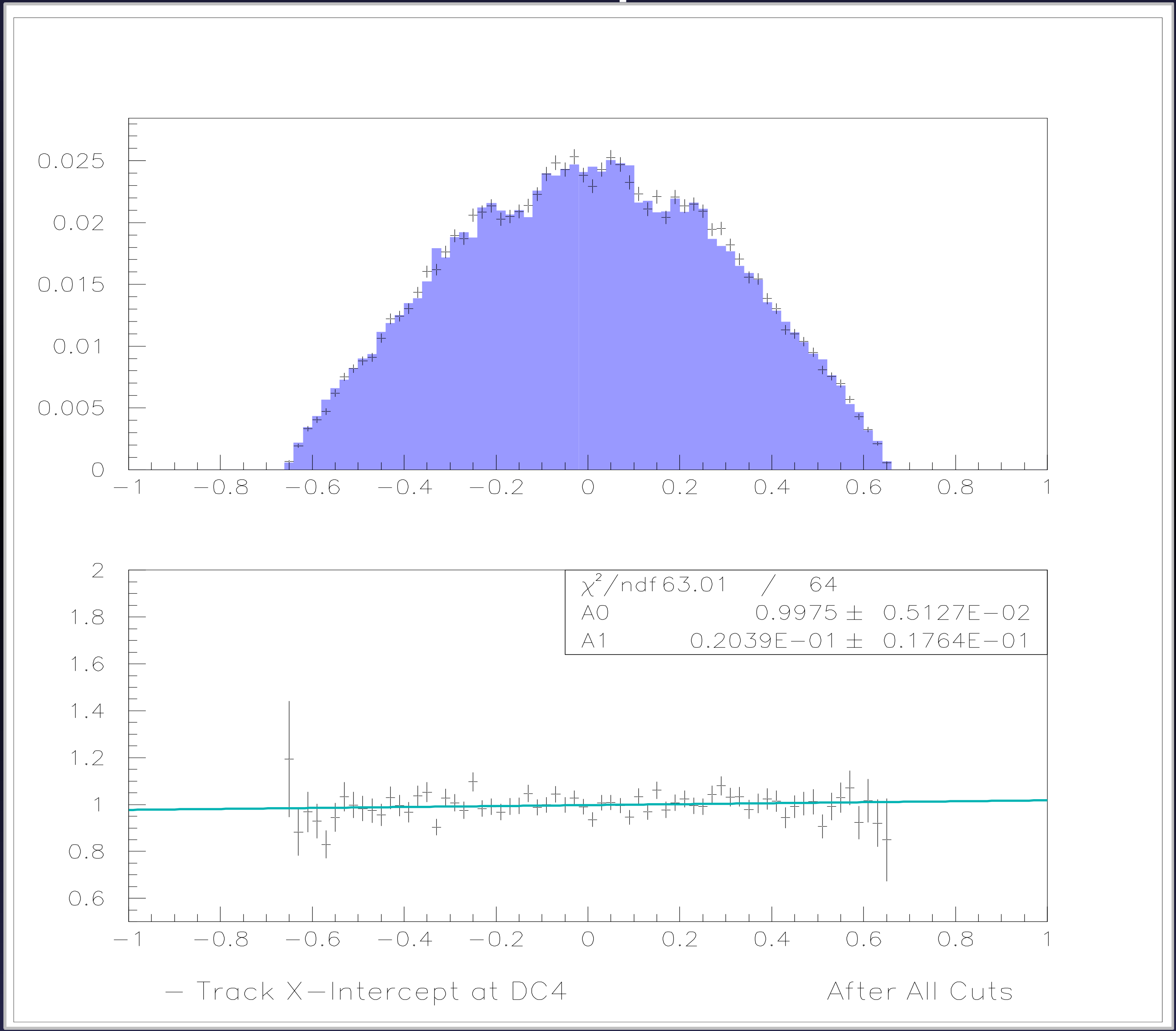
π^+ X Intercept at DC1



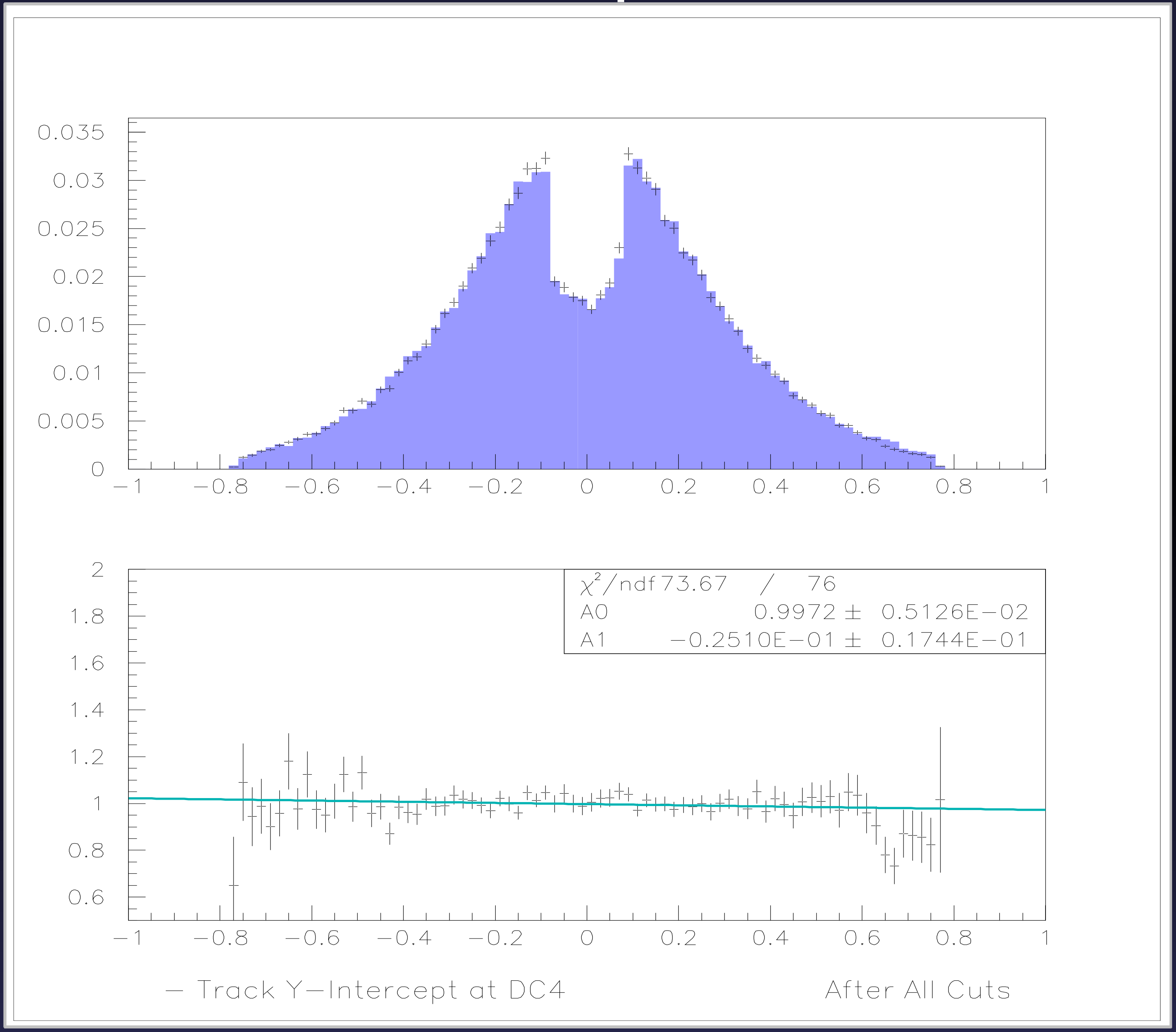
π^+ Y Intercept at DC1



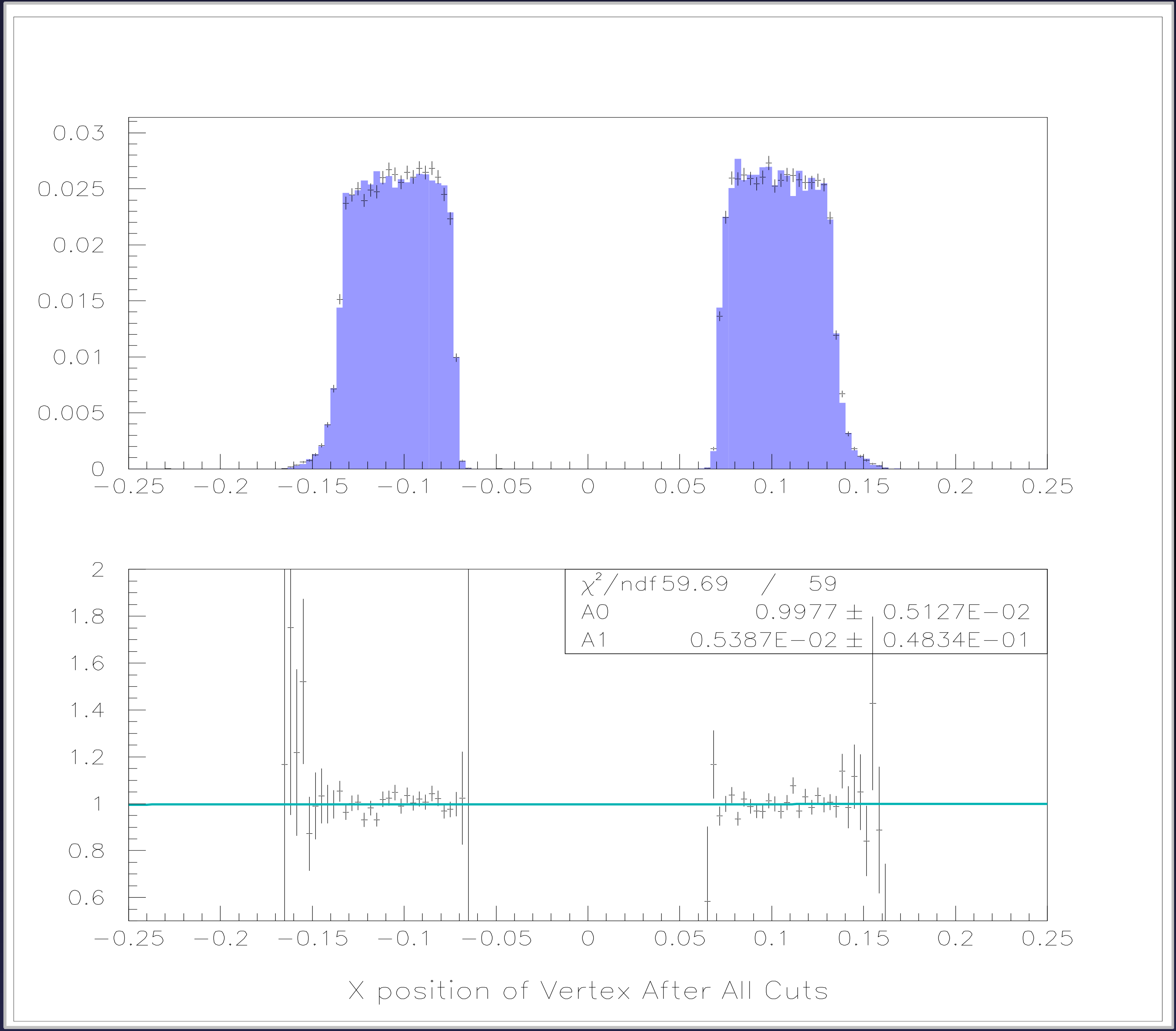
π^- X Intercept at DC4



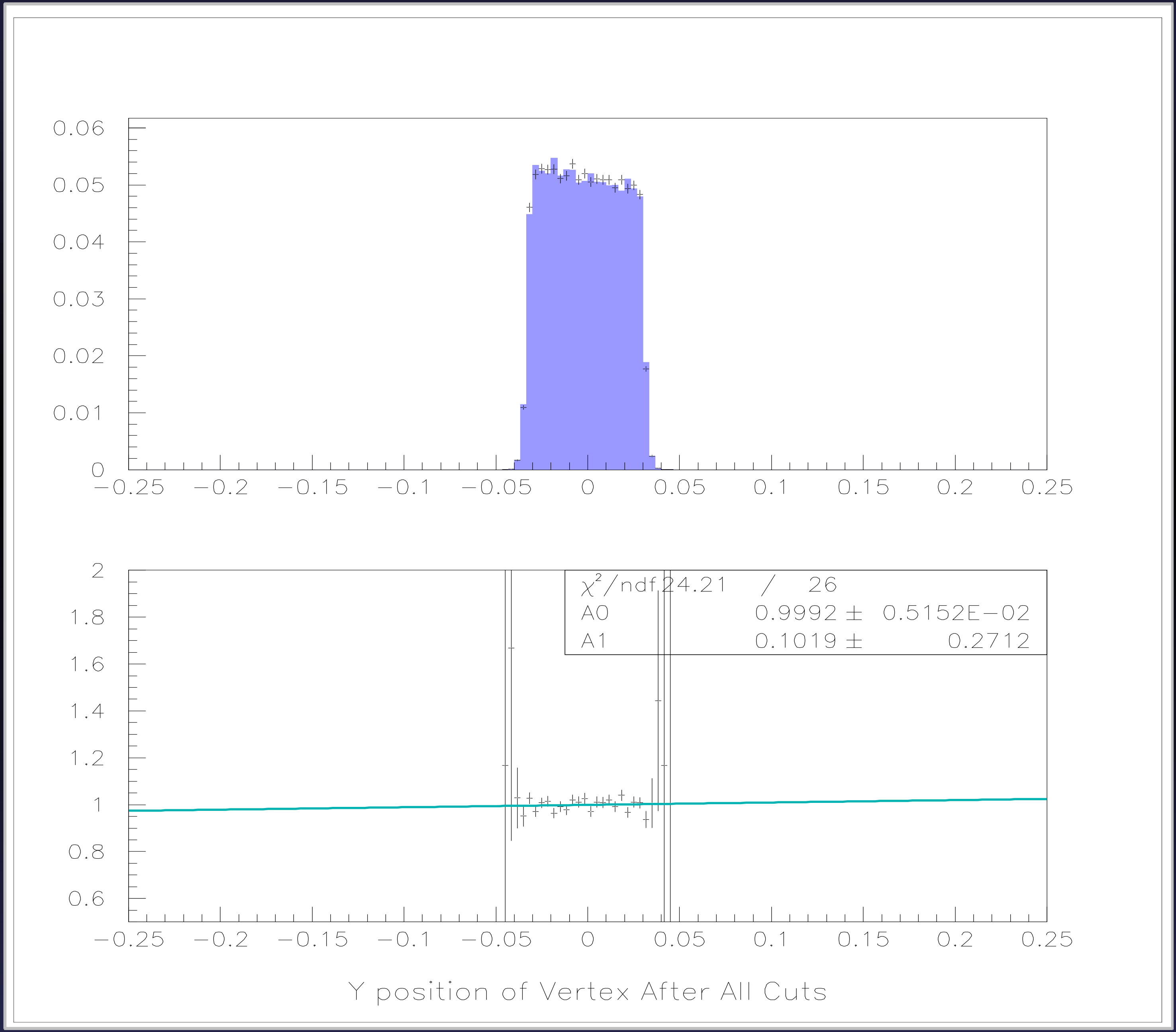
π^- Y Intercept at DC4



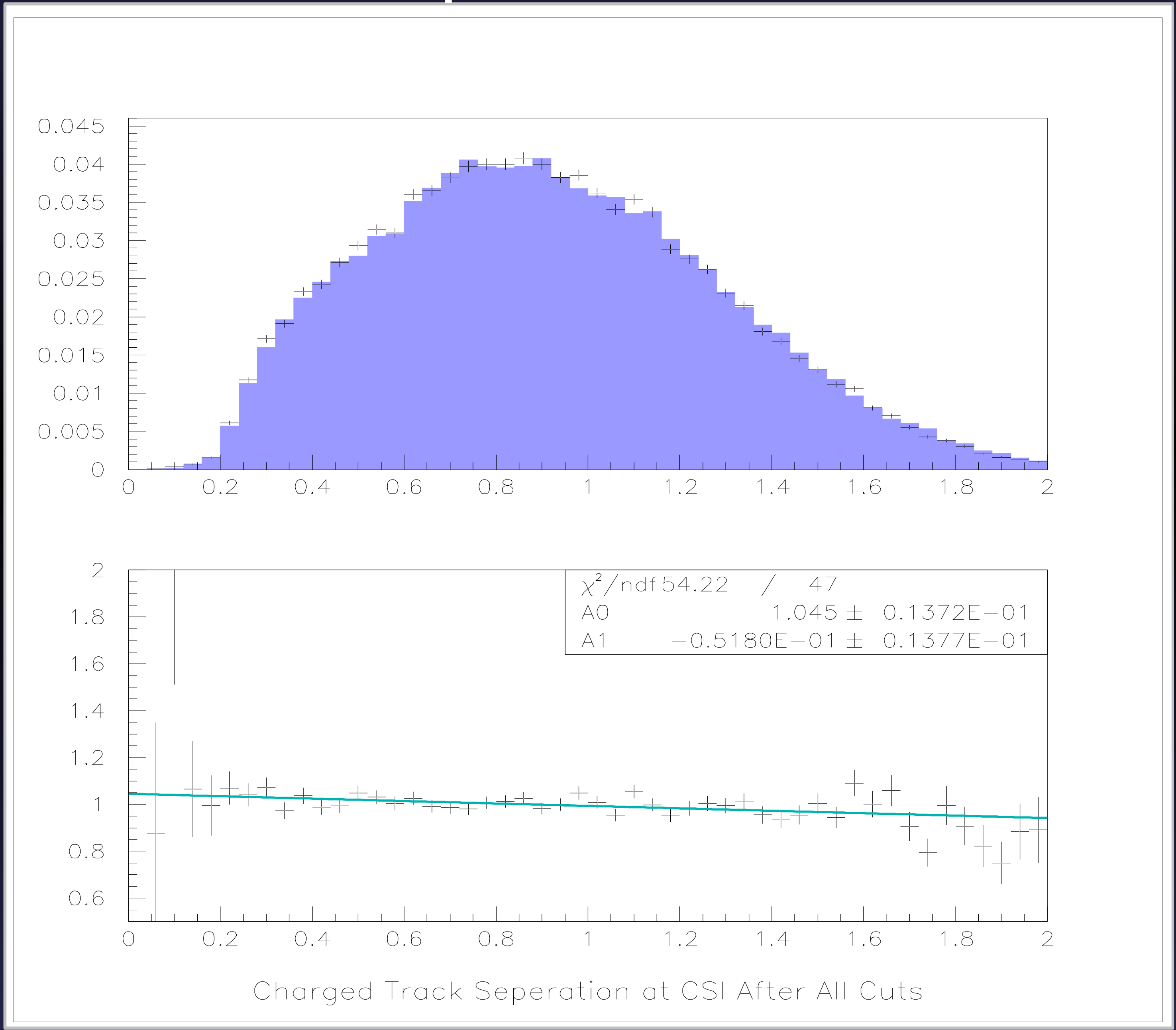
X Vertex


0.03
0.025
0.02
0.015
0.01
0.005
0
−0.25 −0.2 −0.15 −0.1 −0.05 0 0.05 0.1 0.15 0.2 0.25
2
1.8
1.6
1.4
1.2
1
0.8
0.6
χ²/ndf 59.69 / 59
A0 0.9977 ± 0.5127E−02
A1 0.5387E−02 ± 0.4834E−01
−0.25 −0.2 −0.15 −0.1 −0.05 0 0.05 0.1 0.15 0.2 0.25
X position of Vertex After All Cuts

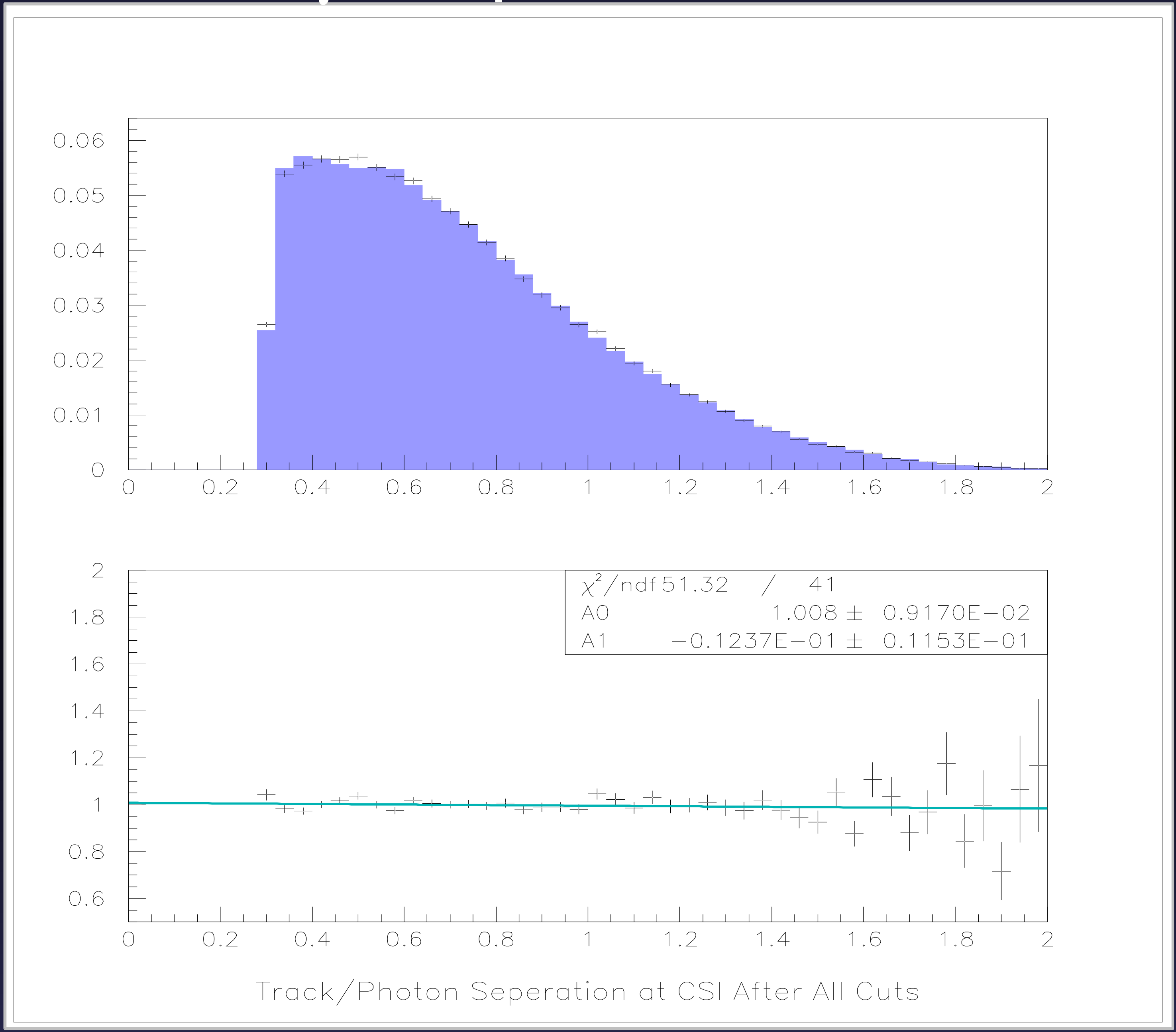
Y Vertex


0.06
0.05
0.04
0.03
0.02
0.01
0
−0.25 −0.2 −0.15 −0.1 −0.05 0 0.05 0.1 0.15 0.2 0.25
2
1.8
1.6
1.4
1.2
1
0.8
0.6
χ²/ndf 24.21 / 26
A0 0.9992 ± 0.5152E−02
A1 0.1019 ± 0.2712
−0.25 −0.2 −0.15 −0.1 −0.05 0 0.05 0.1 0.15 0.2 0.25
Y position of Vertex After All Cuts

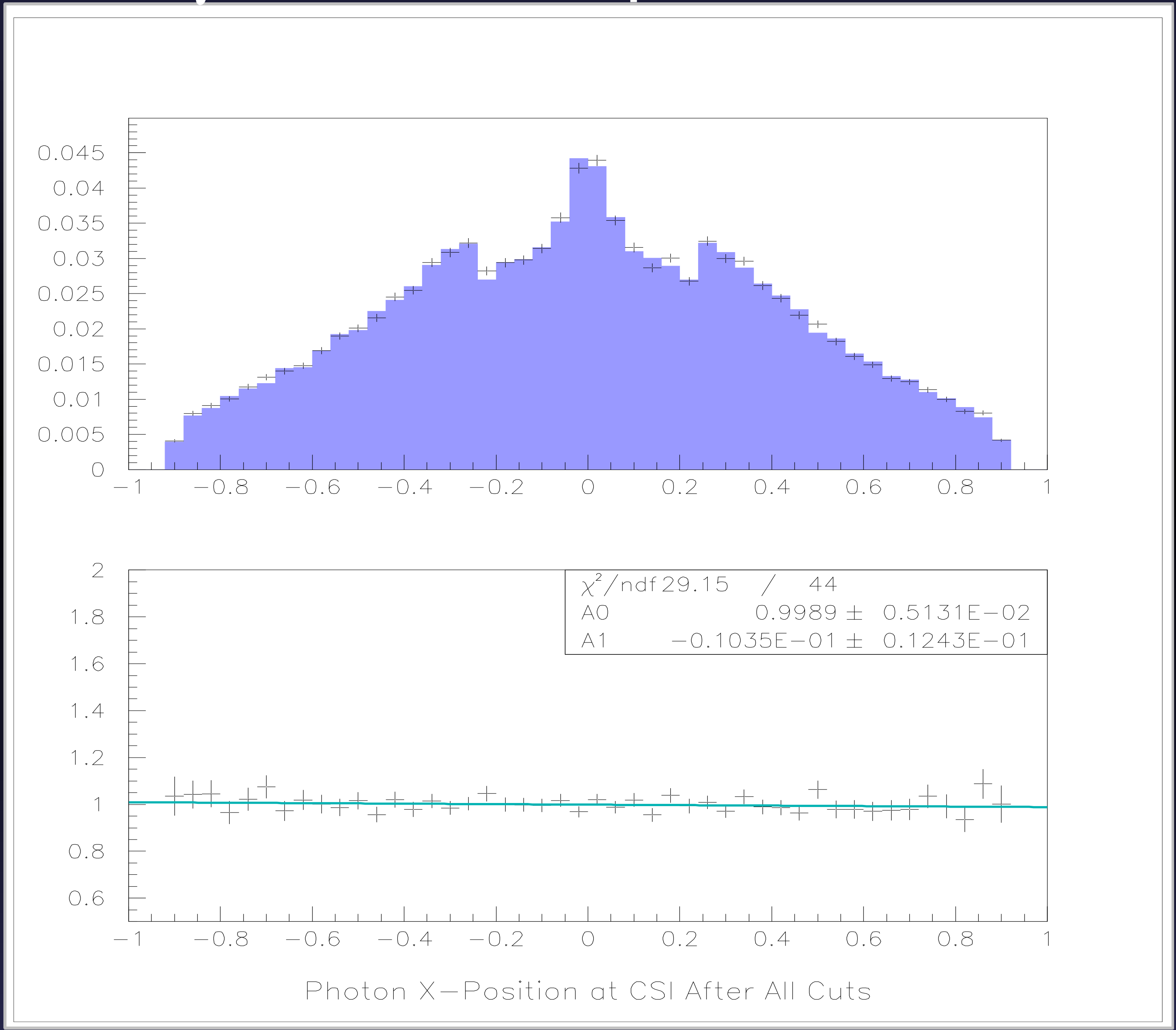
Track Separation at CsI



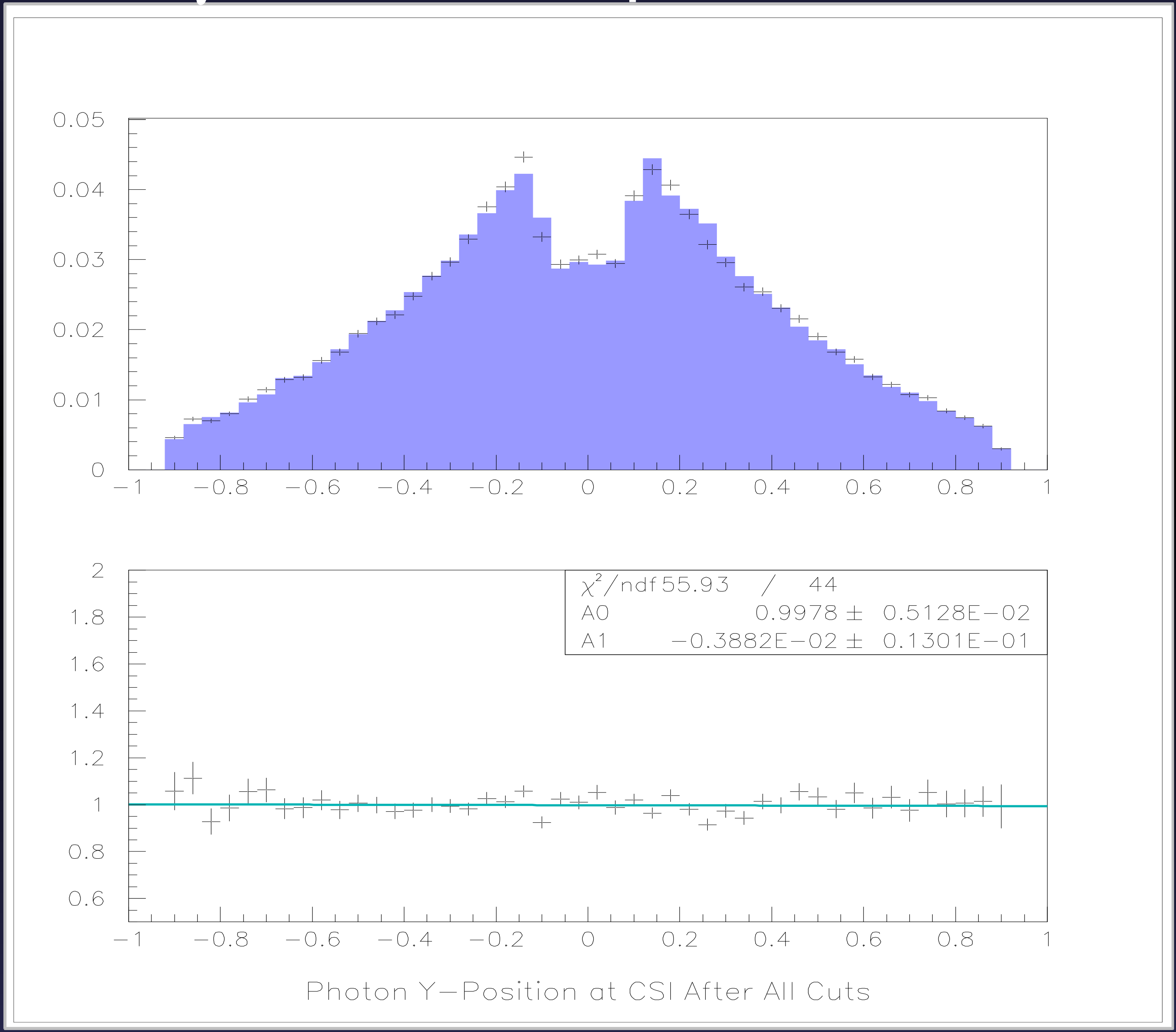
Track/γ Separation at CsI



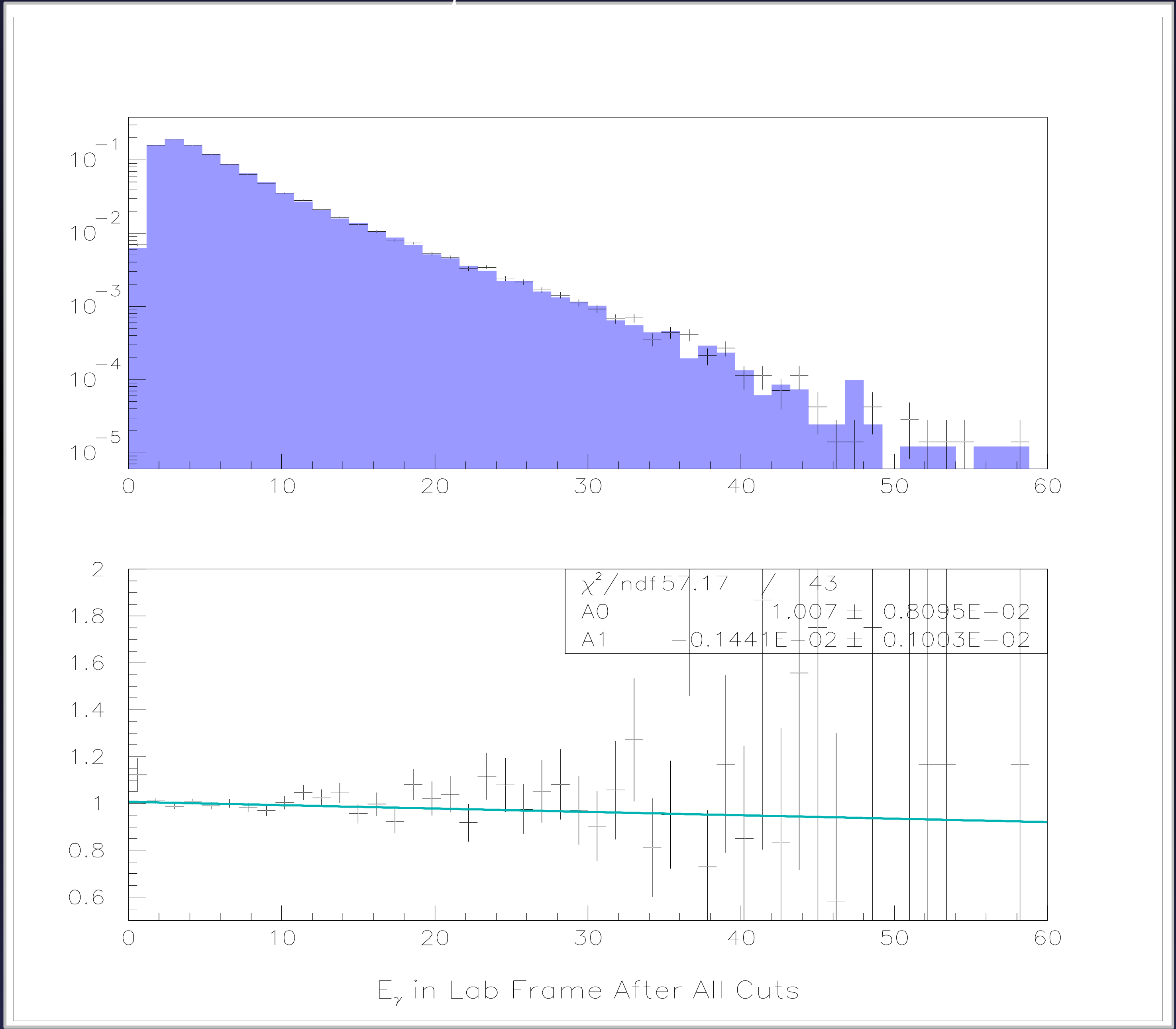
γ X Intercept at CsI



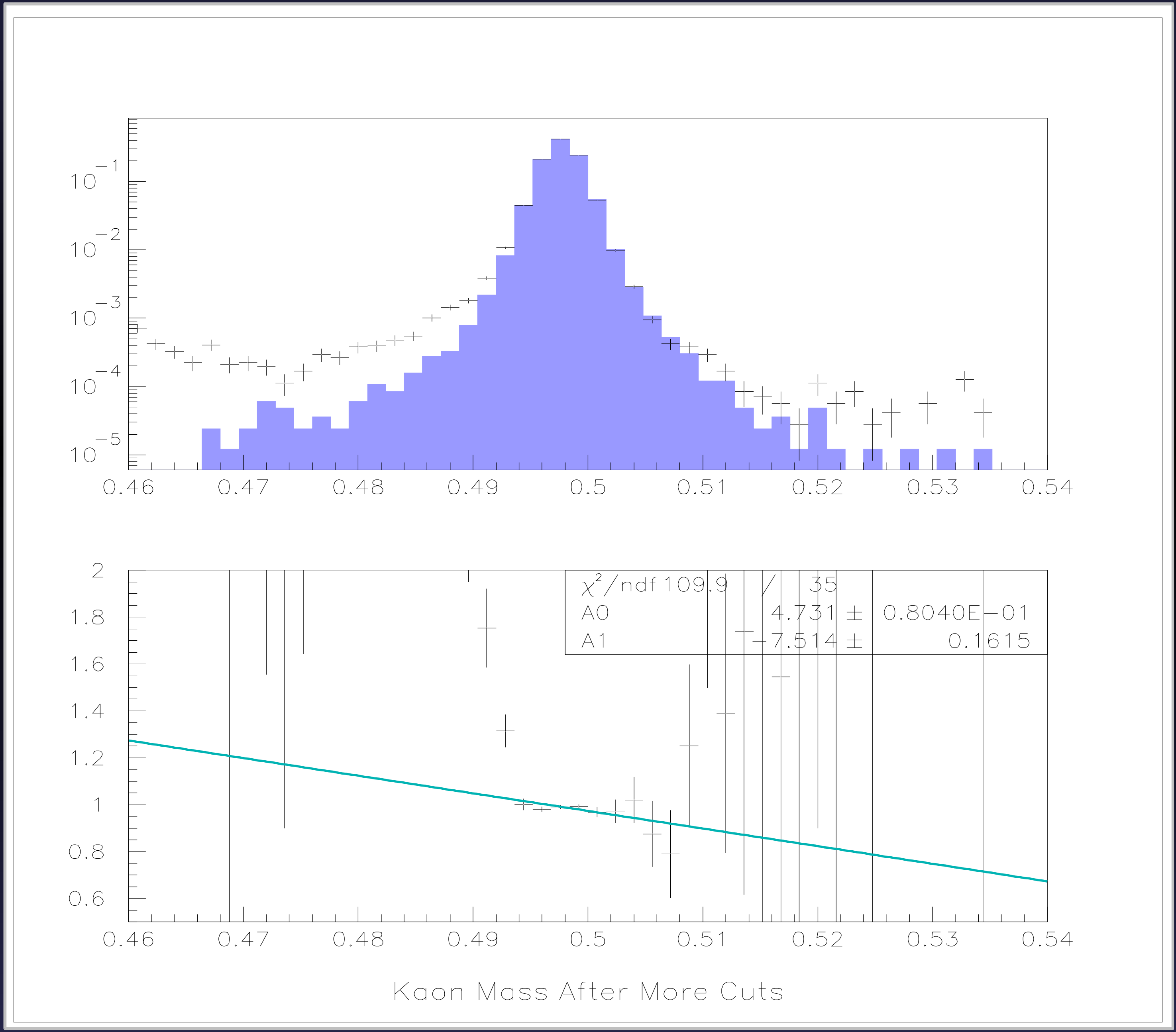
γ Y Intercept at CsI



E_γ in Lab

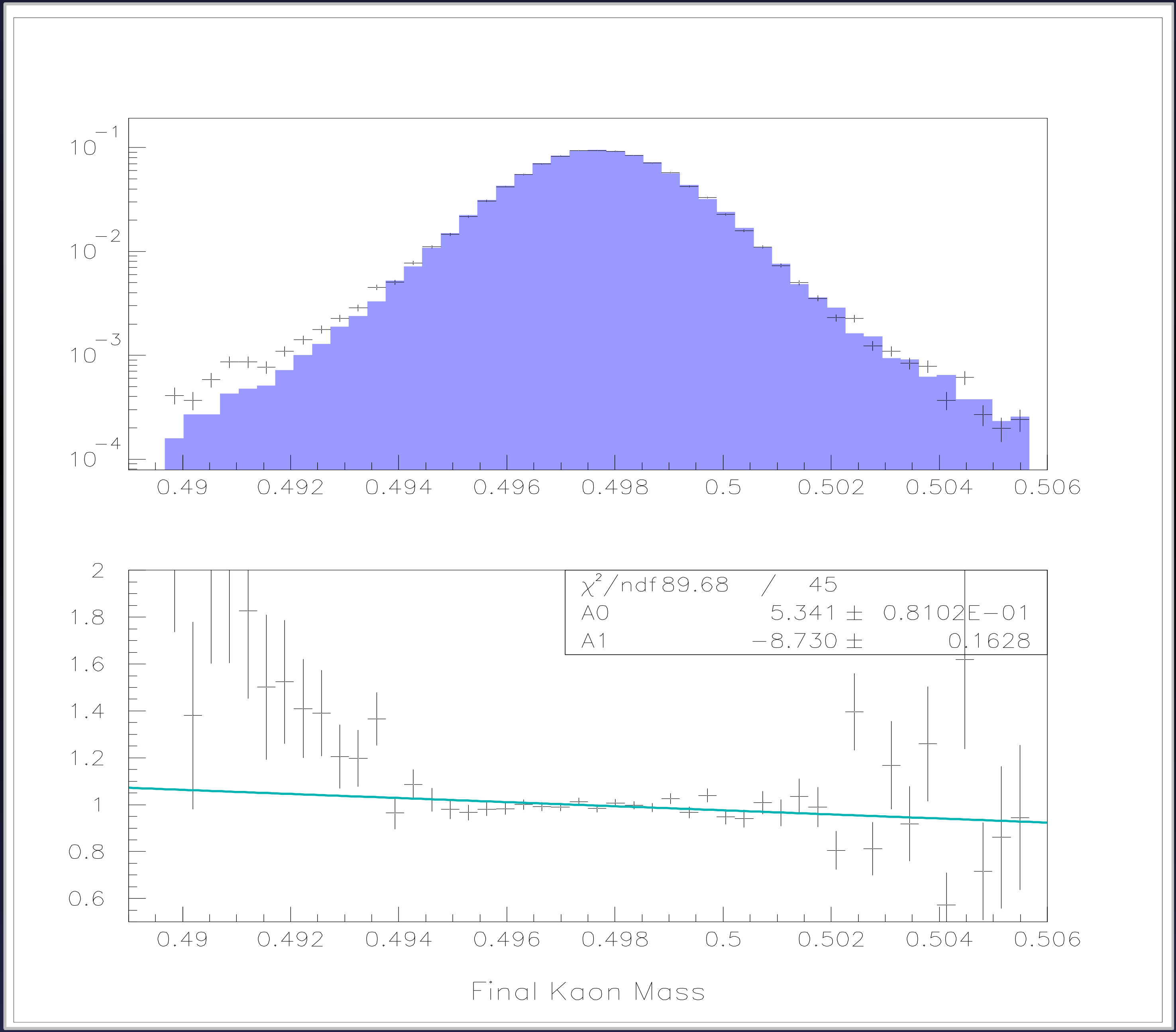


Kaon Mass

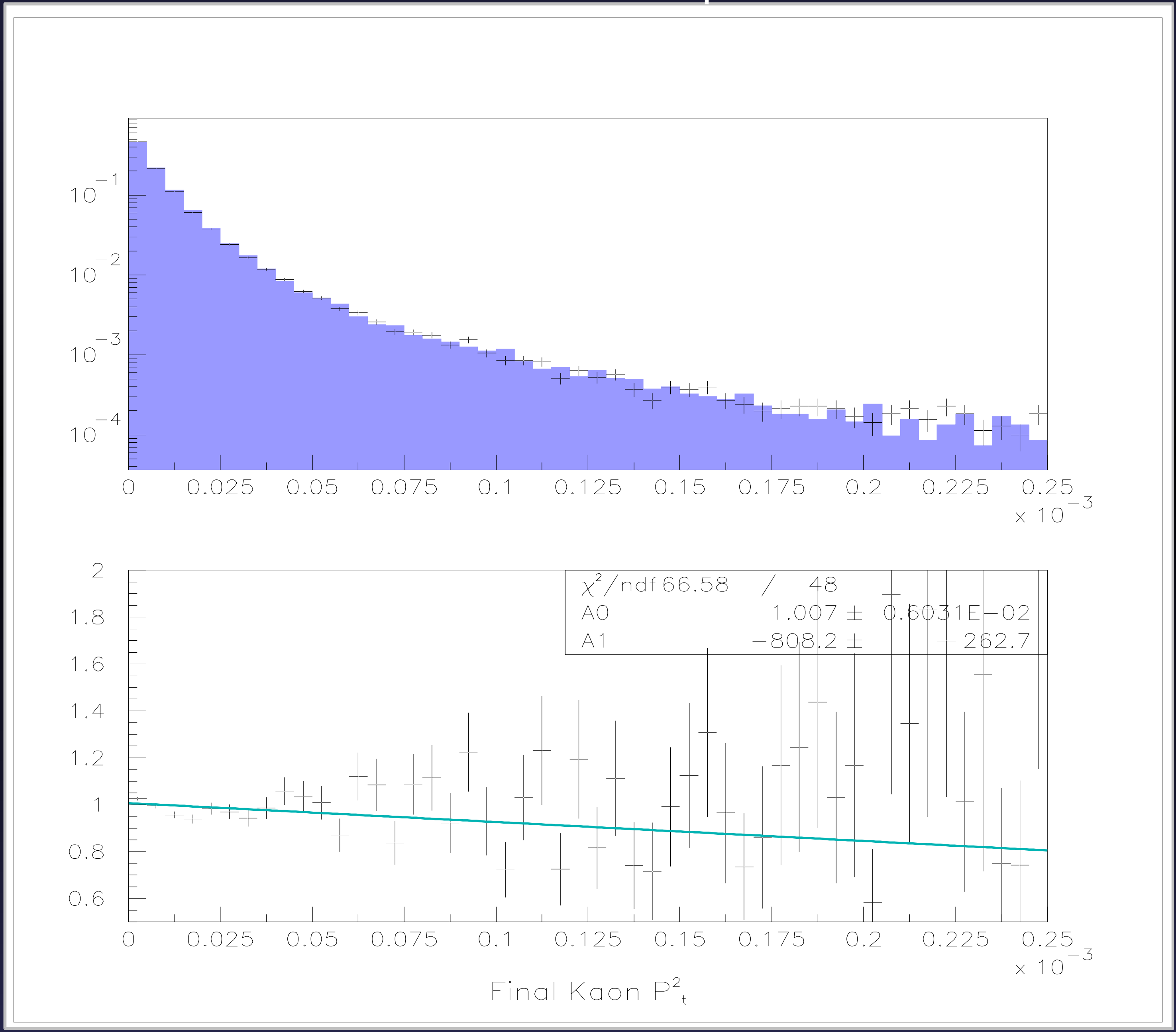


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.46 0.47 0.48 0.49 0.5 0.51 0.52 0.53 0.54
2
1.8
1.6
1.4
1.2
1
0.8
0.6
χ^2/ndf 109.9 / 35
A0 4.731 ± 0.8040E−01
A1 −7.514 ± 0.1615
0.46 0.47 0.48 0.49 0.5 0.51 0.52 0.53 0.54
Kaon Mass After More Cuts

Kaon Mass After Final Mass Cut

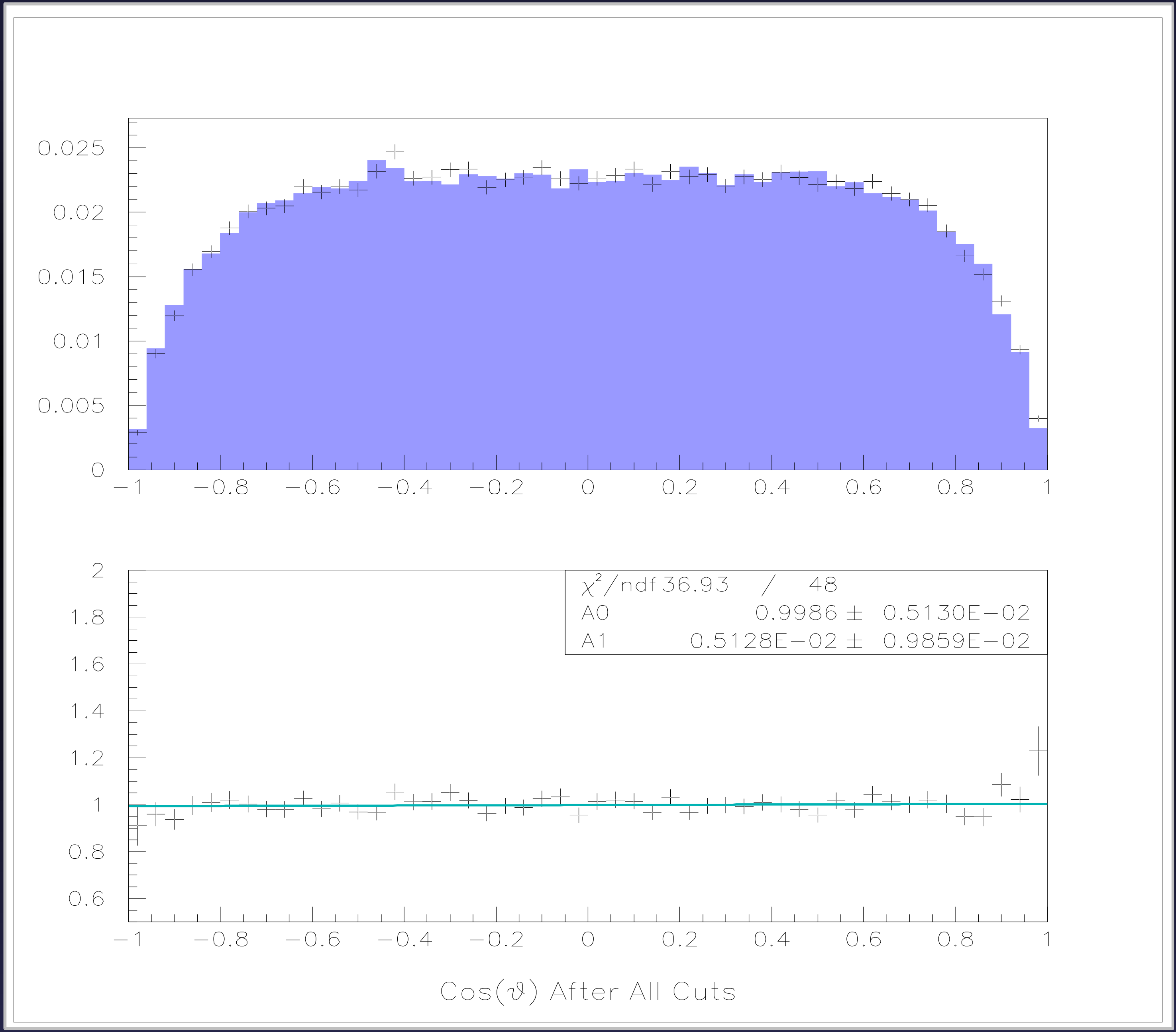


Kaon P_t^2

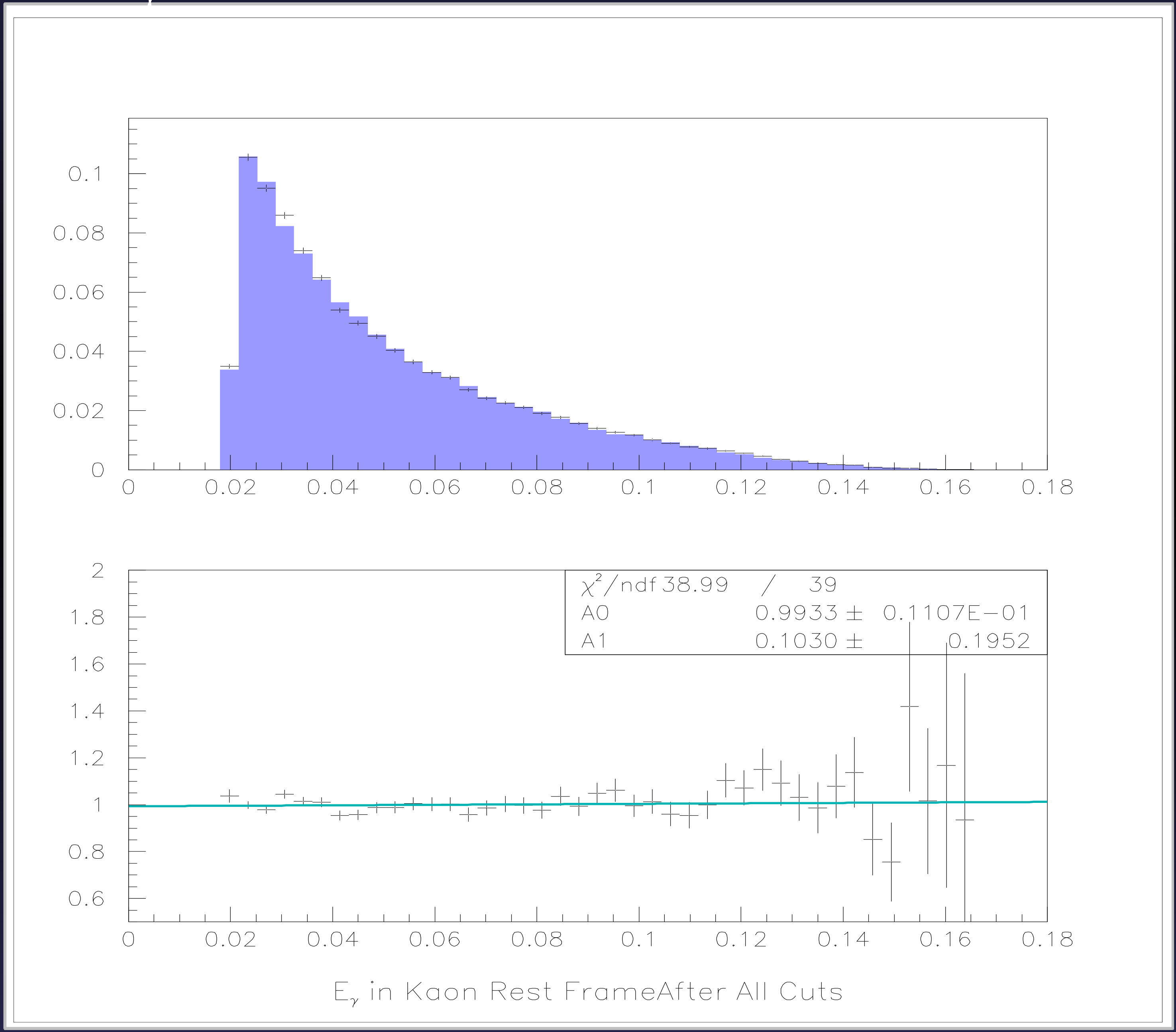


10⁻¹
10⁻²
10⁻³
10⁻⁴
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
0.225
0.25
x 10⁻³
χ²/ndf 66.58 / 48
A0 1.007 ± 0.6031E−02
A1 −808.2 ± 262.7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
Final Kaon P²t

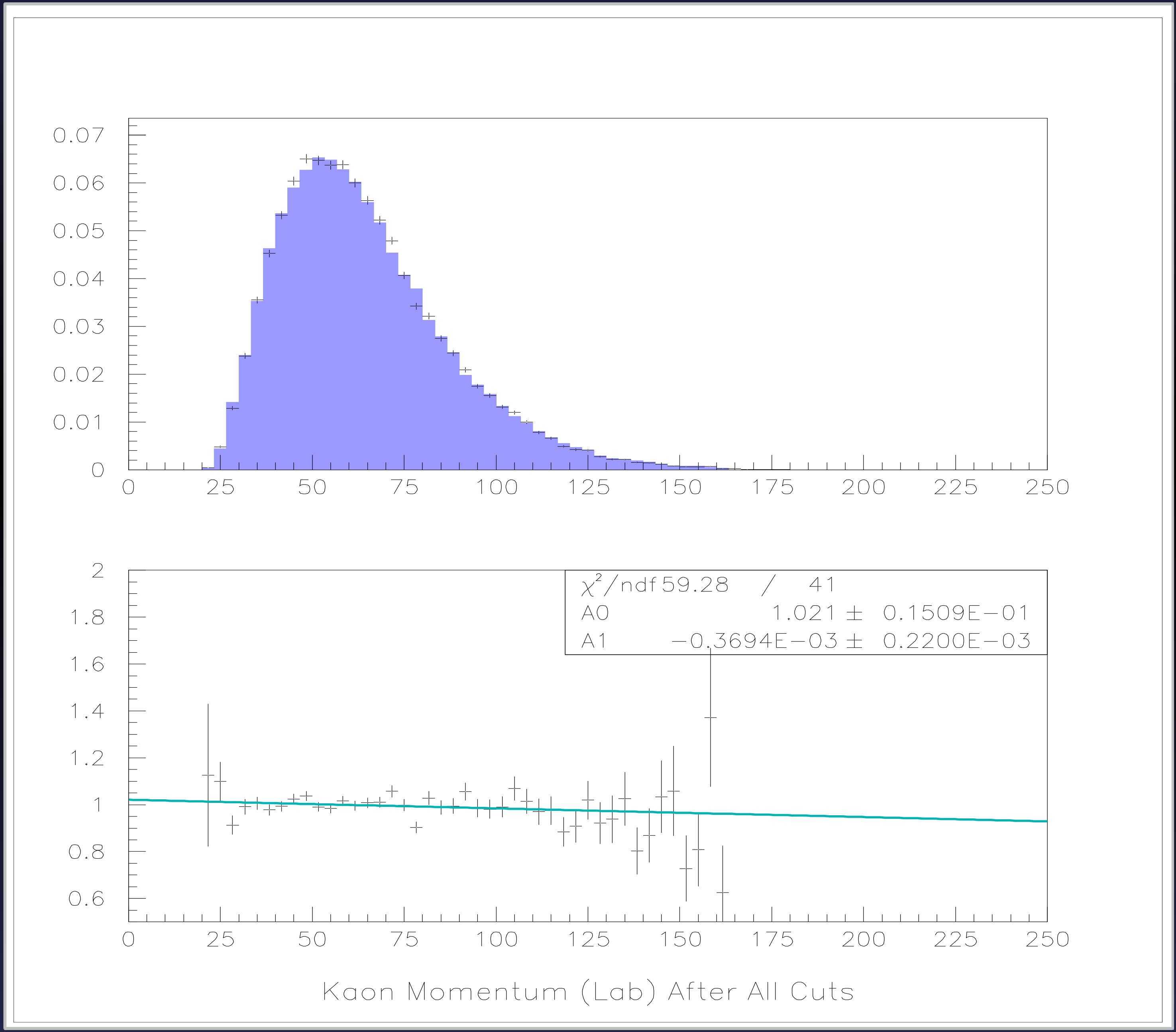
Cosθ


0.025
0.02
0.015
0.01
0.005
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
2
1.8
1.6
1.4
1.2
1
0.8
0.6
χ²/ndf 36.93 / 48
A0 0.9986 ± 0.5130E−02
A1 0.5128E−02 ± 0.9859E−02
Cos(ϑ) After All Cuts

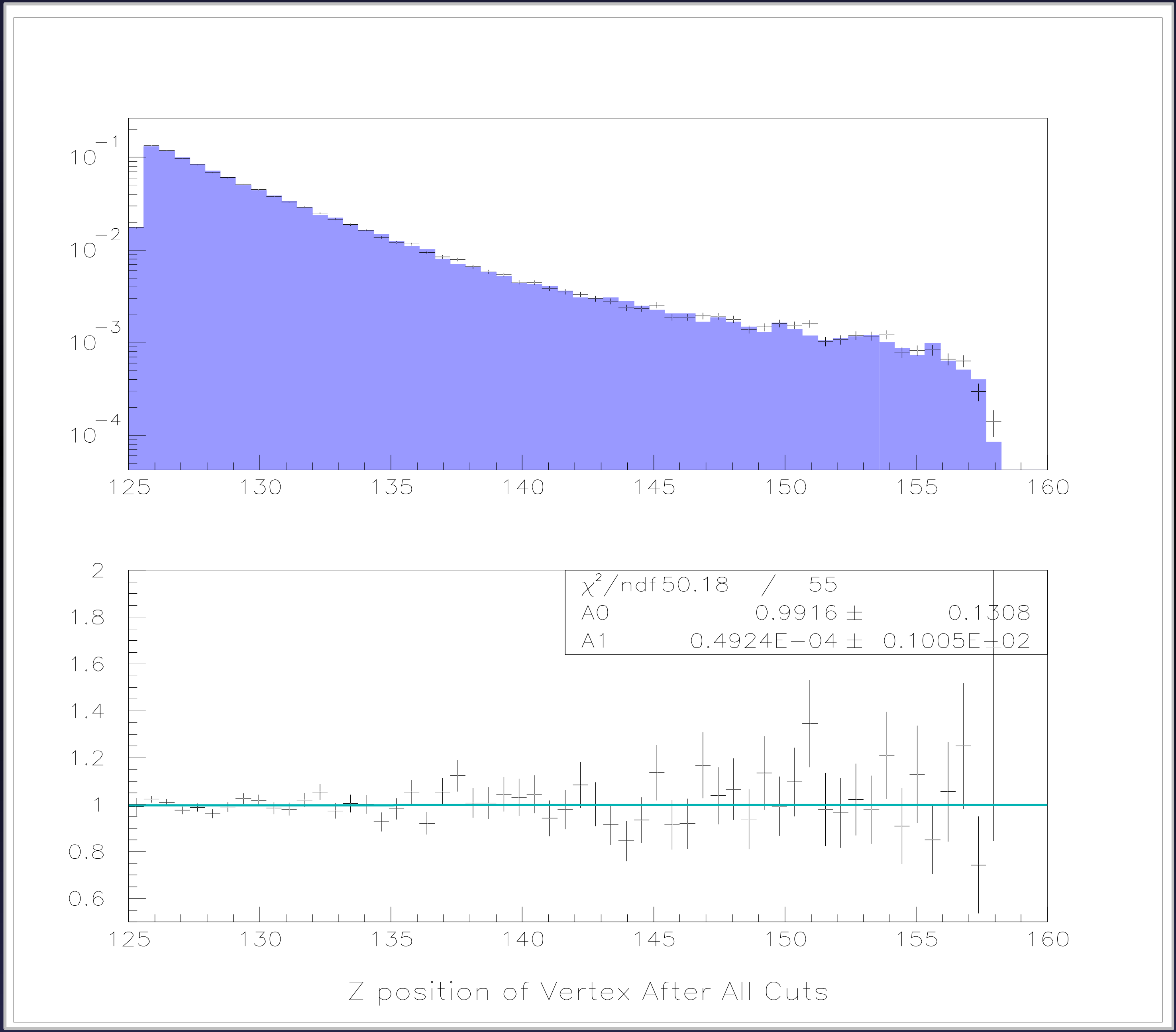
E_γ in Kaon COM Frame



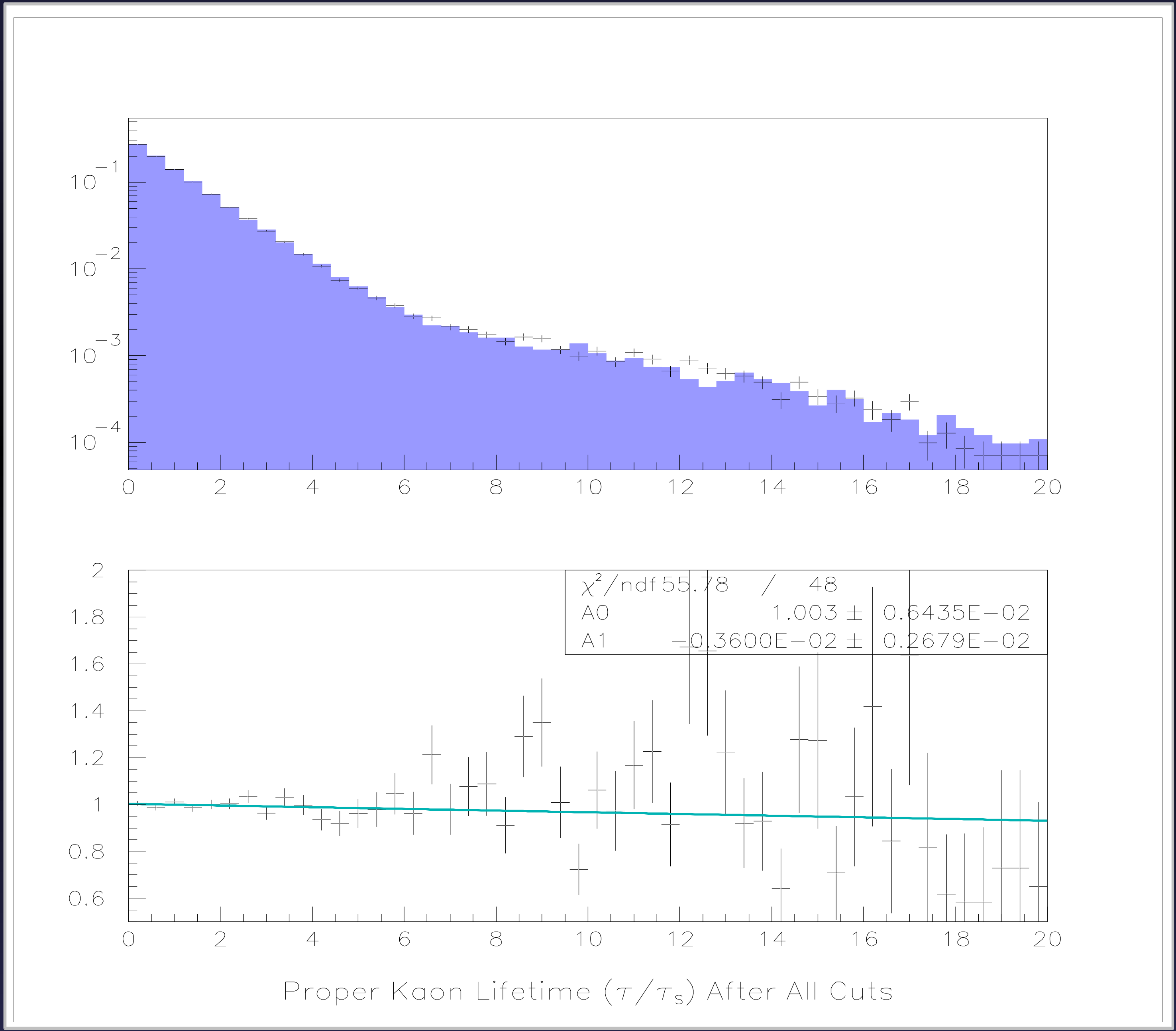
Kaon Momentum



Z Vertex


10^{-1}
10^{-2}
10^{-3}
10^{-4}
125 130 135 140 145 150 155 160
2
1.8
1.6
1.4
1.2
1
0.8
0.6
χ^2/ndf 50.18 / 55
A0 0.9916 ± 0.1308
A1 0.4924E−04 ± 0.1005E+02
125 130 135 140 145 150 155 160
Z position of Vertex After All Cuts

Kaon Lifetime



Summary

- I now have a working Monte Carlo for $K_{L,S} \rightarrow \pi^{+}\pi^{-}\gamma$. It uses a new event generator.
  - So far the results look promising!
- Data/MC studies are ongoing
- Next step is to re- crunch 99 data in order to take care of L3 issues.....